Sub-mesoscale Ocean State Estimation in Shelf/Slope Regions Using Variational Data Assimilation to Integrate Ocean Observing System Data: Application to SW06

Javier Zavala-Garay
Institute of Marine and Coastal Sciences
Rutgers, The State University of New Jersey
New Brunswick, NJ 08901-8521
phone: (732) 932-3433 fax: (732) 932-8578 email: jzavala@marine.rutgers.edu

CO-PI(s) name John L. Wilkin
Institute of Marine and Coastal Sciences
Rutgers, The State University of New Jersey
New Brunswick, NJ 08901-8521
phone: (732) 932-6555x251 fax: (732) 932-8578 email: wilkin@marine.rutgers.edu

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LONG-TERM GOALS

The long term goal is to develop a robust ocean prediction system for the North East US coast that efficiently exploits all the available observational platforms. The system will produce reliable hindcasts of the state of the ocean, and perform also in an operational mode assimilating all available observations in real time and provide estimates of the uncertainty in the deterministic forecast.

OBJECTIVES

To develop a prototype of an operational analysis and dynamical forecast system for mesoscale and sub-mesoscale variability in a coastal transition zone: The Mid-Atlantic Bight (MAB). The system should use advanced data assimilation and adjoint techniques to integrate a high-resolution 3-dimensional coastal model (The Regional Ocean Modeling System; ROMS) with data from a coastal observing system comprised of remotely-sensed Sea Surface Height Anomaly (SSHA) and Sea Surface Temperature (SST), surface current from HF radar (CODAR) installations, autonomous gliders, moorings and XBT/CTD acquired during the ONRs Shallow Water Acoustics 2006 (SW06) field program.

APPROACH

The MAB continental shelf break is characterized by large horizontal and vertical gradients in water properties associated with the shelf break front, a feature susceptible to non-linear instabilities and strong interactions with Gulf Stream warm-core rings that impinge onto the continental slope (Ryan et al., 2001). The broad spectrum of forcing mechanisms that influence the shef-break transition zone

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linking the circulation in the MAB and adjacent deep ocean make the region a challenging laboratory for testing coastal ocean model skill. Therefore the existence of the extensive archive of data acquired during the SW06 field campaign provides an excellent opportunity to test and validate the new data assimilation capabilities of ROMS in a transition area dominated by two different circulation regimes, and to prototype an adjoint-based operational ensemble system. To this end, two principal research tasks are proposed: (i) implementation of a data-assimilative analysis system in a region having two differing circulation regimes (the costal zone and adjacent deep ocean), and (ii) implementation of an efficient yet rigorous ensemble forecast system that exploits the known statistical properties of the atmospheric weather or stochastic forcing of the region. These two topics are related through their use of a common set of modeling tools; namely, the tangent linear and adjoint versions of the nonlinear operator of ROMS. In the case of data assimilation, these codes underpin the formulation of strong-constraint 4-dimensional variational methods that allow the incorporation of any data that are a function of the model state variables. In the case of ensemble forecast system, a variant of the adjoint sensitivity driver is used to estimate the possible divergence of model forecasts due to errors in the initial conditions and the action of atmospheric weather, which highly affects the coastal zone and, due to its inherent chaotic nature, in an operational framework is not known beyond a few days.

WORK COMPLETED

Task 1: Limited area ROMS configuration: A limited area ROMS model encompassing the MAB and adjacent deep ocean region was configures by J. Wilkin. The ESPreSSO (Experimental System for Predicting Shelf and Slope Optics) prototype system has a 5-km horizontal, 36-sigma levels resolution. Atmospheric forcing data are taken from the North American Mesoscale (NAM) forecast system operated by NCEP. NAM is an implementation of WRF-NMM for the North American continent and adjacent seas, with a horizontal resolution of approximately 15 km. ROMS uses NAM surface air temperature, pressure and relative humidity, 10-m vector winds, rain, downward longwave radiation, and net shortwave radiation, to specify surface fluxes of momentum and buoyancy using standard bulk formulae. Real-time river runoff is prescribed from USGS river gauges, and open boundary conditions are taken from another ROMS application developed by Dr. Ruoying He that considers the MAB and Gulf of Maine region, and includes data-assimilative HYCOM at the boundaries and nudging to observed SST. We are currently also experimenting with a bias-corrected boundary forcing from HYCOM, since this product is available in real time. The ESPreSSO application produces a reasonable seasonal cycle but fails in producing adequate mesoscale variability. This fact is illustrated in Fig 1a that compares the SSH standard deviation of the model with that of the altimeter data.

Task 2: Development of an operational data assimilation system: We have prototyped an Incremental Strong-constraint 4-Dimensional Variatonal (IS4DVAR) data assimilation system for the ESPRESSO application. This task required selection of appropriate parameters such as appropriate decorrelation scales used in the IS4DVAR algorithm, number of iterations needed to converge to the minimum of the model misfit, refinement of the weighting of background and observation contributions to the cost function misfit, length of the assimilation window, etc. It also required considerable work in the collection and quality control of the observational products to be assimilated. The skill of the deterministic forecast (a single integration of the nonlinear model after data assimilation) is being quantified for years 2006 and 2007 where extensive data has been collected by our group during the past year.

Task 3: Development of an adjoint-based ensemble prediction system. We are now experimenting with ensemble forecast system to determine whether there are persistent regions where uncertainty in the model state impacts predictive skill. A novel component of this project is the use of the adjoint model to estimate the expected variability of selected indices of the model forecast due to the action of atmospheric weather in an operational forecast system. The methodology is based on the use of a variant of the adjoint sensitivity analysis and it allows estimation of the uncertainty in the predicted indices using a few integrations of the adjoint model, in remarkable contrast with the direct method based on a large number of integrations of the forward model which in an operational framework is difficult to perform. The indices are chosen based on the application of interest such as a metric quantifying interchange of tracers across the shelf-break, the strength of shelf-break fronts (which coincide with regions of high acoustic uncertainty), the dispersion of a passive tracer (e.g., a contaminant), stratification in a selected area, or expected uncertainty in the predicted patterns of currents. The addition of this final component will prototype a fully operational dynamical/statistical forecast system in a coastal transition zone that are of increasing interest to Navy operational requirements.

RESULTS

The system is now assimilating satellite SST and altimeter data, hydrographic data from gliders, XBTs and CTDs, and we are finally experimenting with assimilation of surface currents from the existing high frequency radar (CODAR) array.

This year a lot of progress was made by including all these data streams into the assimilation system, but perhaps the one that we learned the most was the assimilation of along track data. It is a common practice to assimilate gridded SSH products into ocean models. This is a good approximation in regions where mesoscale eddies have a long relatively isotropic length scales of the order of hundreds of km (Wilkin et al, 2002). SSH in coastal regions exhibits length and time scales that are shorter and more strongly anisotropic than in the deep ocean due to flow-bathymetry interactions. This presents challenges to statistically-based methods (e.g. optimal interpolation) typically used to produce spatial gridded maps from along-track data (Ducet et al., 200). Our approach therefore was to use variational methods to assimilate the along-track data into the ESPreSSO domain instead of the gridded products. The decision was also motivated by the fact that for the MAB there are strong differences between the along-track data and the AVISO gridded product. This difference is due partly to smoothing in time by the optimal interpolation, but principally because of the anisotropy of variability where GS rings interact with the bathymetry of the continental shelf. A number of unanticipated details methodologies were needed in order to implement the assimilation of alongtrack data in the ESPreSSO application, which are described next.

Dynamic topography: ROMS assimilates total SSH which is the sum of the mean SSH (or dynamic topography) plus the SSH anomaly due to mesoscale activity plus the tides. It is a common practice to use long term mean of the integration of the model as a proxy for the dynamic topography. We found however that even small biases in the model vertical structure of temperature and salinity will be noticeable in the mean SSH. More important, assimilation of SSH in a biased profile results in an incorrect vertical projection of the SSH. Therefore the Mean Dynamic Topography (MDT) was computed by IS4DVAR analysis of a regional high-resolution (4 km) 3-dimensional temperature and salinity climatology computed from historical hydrographic data by a member of our group. This MDT and the climatology itself (with appropriate error bars) was included in the assimilation experiments.

Tides: In IS4DVAR, when forming the weighted sum of model-data misfit that constitutes the cost function to be minimized, variation in the time dimension during the analysis interval is fully accounted for by sampling the model at the precise time and location that the observations were made. Any mismatches at high frequency in the modeled and observed SSHA therefore enter into the cost function. This is potentially problematic in coastal waters where the oceanic response of sea level to tidal and other high frequency forcing is substantially greater than in regions where sub-tidal frequency mesoscale variability dominates the dynamics. Anticipating the possibility that even small phase errors in the modeled and observed tide could overwhelm the IS4DVAR procedure (note that, uncorrected, altimetry observations include the instantaneous signal of sea level variability associated with the local tide), we took the following approach. A 1-year long ROMS simulation without assimilation, forced by observed tidal harmonics (Egbert et al., 2002) on the model perimeter, was run to compute the model's tidal harmonic sea level response. Next, the default corrections provided in the Radar Altimeter Database System (RADS; http://rads.tudelft.nl) were applied to de-tide the along-track altimeter data. Finally, the ROMS model tide harmonics were interpolated to the altimeter ground-track positions and used to introduce ROMS tidal variability to the altimeter data prior to assimilation. Thus the observations are adjusted to include the modeled tide. By this approach, SSH variability associated with tides is the same in the model and adjusted data, and therefore will not enter into the IS4DVAR cost function; the model-data misfit in SSH is then dominated by processes other than the tides. It is these processes, such as the SSH variability associated due to mesoscale eddies in the Slope Sea and movements of the Gulf Stream and shelf-slope fronts that we wish to correct and project to mesoscale variability in the subsurface density and velocity field.

Filtering of the barotropic mode. The adjoint model can erroneously accommodate too much of the SSH model-data misfit in the barotropic mode, which sends fast gravity waves along the model perimeter. We therefore acknowledge the temporal correlation of the sub-tidal altimeter SSH data by repeating (duplicating) the altimeter SSH observations at $t = -6$ hour, $t=0$ and $t = +6$ hours, but with appropriate time lags in the added tide signal. These data cannot easily be matched by a barotropic wave.

The benefit after assimilation of the altimeter data is illustrated in Fig 1 which compares the variance of the non-assimilative model versus that after assimilation.

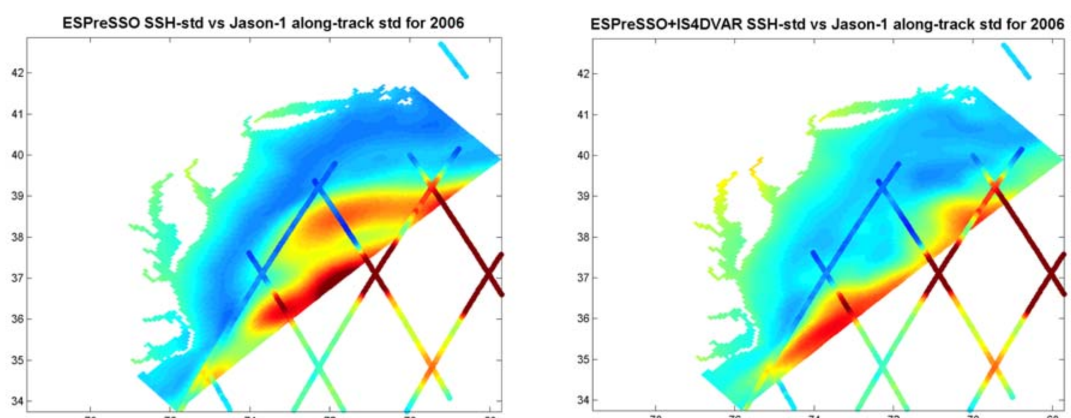

Figure 1: Standard deviation of the ESPreSSO application without (left) and with (right) data assimilation of altimeter data for 2006.

The impact of the assimilation of SSH and SST in forecasting non-assimilated temperature profiles is illustrated in Fig 2, where all the temperature profiles for 2006 where ranked by water depth and plotted along with the ESPreSSO model predictions.

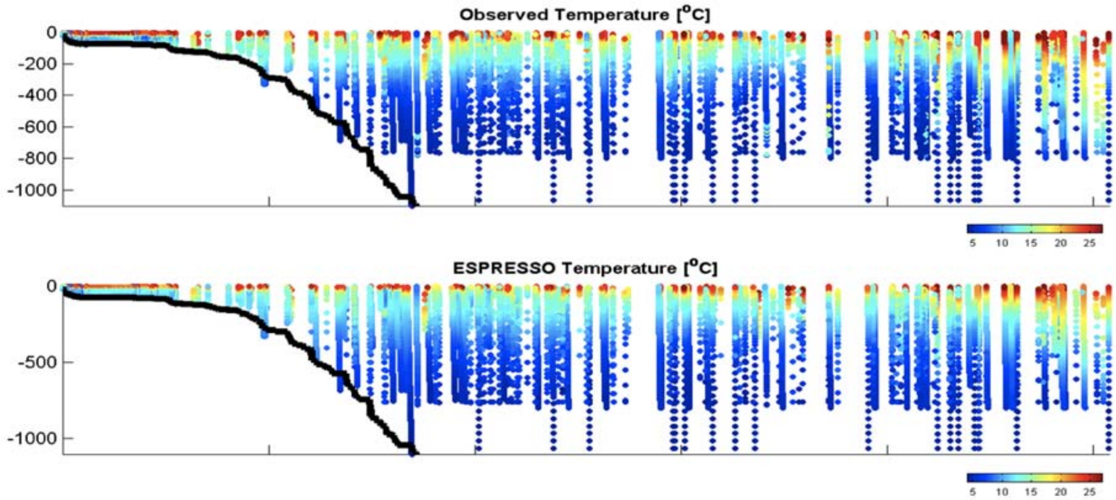

Figure 2: ESPreSSO hindcast of observed temperatures for different water depths during 2006. Satellite information (SSH and SST) was only assimilated.

IMPACT/APPLICATIONS

We are now experimenting with assimilation of real time data streams, which will allow us to deliver real time forecast for the MAB region. This system is scheduled to start as a prototype in Nov 2009 and the forecasts will be posted at http://www.myroms.org/espresso/.

TRANSITIONS

We have now produced a first version of reanalysis for 2006 and this reanalysis has been made available to the community through an OPeNDAP server at http://www.myroms.org/espresso/. As we progress refining the reanalysis we will be posting the updated versions in the same webpage. The scientific findings will be published in scientific journals after the evaluation of the system is completed.

RELATED PROJECTS

This project will benefit from a related ongoing project supported by NASA-OSTS to extend the SSH data stream into the MAB shelf through refined reprocessing of the altimeter.

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